Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method)

N. Doerfliger · P.-Y. Jeannin · F. Zwahlen

Abstract Groundwater resources from karst aquifers play a major role in the water supply in karst areas in the world, such as in Switzerland. Defining groundwater protection zones in karst environment is frequently not founded on a solid hydrogeological basis. Protection zones are often inadequate and as a result they may be ineffective. In order to improve this situation, the Federal Office for Environment, Forests and Landscape with the Swiss National Hydrological and Geological Survey contracted the Centre of Hydrogeology of the Neuchâtel University to develop a new groundwater protection-zones strategy in karst environment. This approach is based on the vulnerability mapping of the catchment areas of water supplies provided by springs or boreholes. Vulnerability is here defined as the intrinsic geological and hydrogeological characteristics which determine the sensitivity of groundwater to contamination by human activities. The EPIK method is a multi-attribute method for vulnerability mapping which takes into consideration the specific hydrogeological behaviour of karst aquifers. EPIK is based on a conceptual model of karst hydrological systems, which suggests considering four karst aquifer attributes: (1) Epikarst, (2) Protective cover, (3) Infiltration conditions and (4) Karst network development. Each of these four attributes is subdivided into classes which are mapped over the whole water catchment. The attributes and their classes are then weighted. Attribute maps are overlain in order to obtain a final vulnerability map. From the vulnerability map, the groundwater protection zones are defined precisely. This method was applied at several sites in Switzerland where agriculture contamination problems have frequently occurred. These applications resulted in recommend new boundaries for the karst water supplies protection-zones.

Key words Karst aquifer · Groundwater · Aquifer protection · Vulnerability · GIS

N. Doerfliger (✉)
BRGM National geological survey, F 34000 Montpellier, France

P.-Y. Jeannin · F. Zwahlen
Center of Hydrogeology, Institute of Geology, University of Neuchâtel, 11 rue E-Argand, CH-2007 Neuchâtel, Switzerland

General background

Introduction

Karst aquifers are generally considered to be particularly vulnerable to pollution, because of their unique structure. This structure is strongly heterogeneous. It can be considered as a network of conduits of high permeability surrounded by large volumes of low permeability rock. Recharge occurs by both dispersed and concentrated water entry. This implies that a fair amount of the recharge infiltrates directly into the conduit network so that attenuation of contaminants does not occur effectively as in porous aquifers. It can be pointed out that the percentage of concentrated recharge increases with increasing recharge, therefore, the water quality can still be good at low water level stage.

Applying the present Swiss regulations for defining water supplies protection-areas in karst environments leads to many protection areas which are too large and not pertinent. Porous media protection areas are outlined by a 10 days transit time limit (zone 2). Due to the heterogeneity of groundwater velocity in karst environment and to the impossibility for cost purpose to carry out many tracer experiments, zone 2 should include the whole catchment. As land use restrictions in zone 2 are too restrictive, in most cases the whole catchment is assigned to zone 3. Consequently zone 2 is either not present or too small. As a result, water quality problems have occurred. For this reason, the concept of vulnerability mapping using a multi-attribute approach, the EPIK method, has been developed. The EPIK method was developed to assess the

intrinsic vulnerability of groundwater to surface contamination and to provide a tool to define the protection zones in karst environments for hydrogeological consulting. (Intrinsic vulnerability represents the inherent hydrogeological and geological characteristics which determine the sensitivity of groundwater to contamination by human activities. Intrinsic vulnerability refers essentially to risk associated to non-point sources. Intrinsic vulnerability as opposed to specific vulnerability considers all kind of contaminants.) The most recent version is an update of an earlier paper about EPIK (Doerfliger and Zwahlen 1995). It now includes new values of weighting and ranking. This EPIK method is an overlay weighting and rating method similar to that of DRASTIC developed by Aller and others (1987).
In many countries vulnerability maps are established on a large scale, e.g. regional, county or state scale. To our knowledge, EPIK is the first method to suggest vulnerability mapping of karst systems at catchment scale, which allows the determination of groundwater protection areas. Based on a hydrogeological conceptual model of karst hydrological systems, EPIK is a method that takes into account the most significant parameters considered in this model. Some results of vulnerability mapping and protection areas based on the EPIK approach on one test site in Swiss Jura are presented in this paper.

Current Swiss groundwater protection legislation

The Swiss legislation to protect water – 1991 Federal Law on Water Protection – requires defining protection zones in the vicinity of public drinking water supplies. According to the regulations, three different zones have to be delineated:

1. S1 zone: This zone has to protect the water supply structure against damage and to prevent any direct penetration of contaminants into the groundwater.
2. S2 zone: this zone has to provide protection against microbiological and non-degradable contaminants and to allow enough time for intervention in the case of an accident.
3. S3 zone: this zone has to provide additional safety. It could in many cases, correspond to the rest of the catchment not covered by zones S1 and S2.

The three zones are subject to specific land-use restrictions according to the protection objectives. Today, the definition of the protection zones for all water-catchments in Switzerland is almost completed. But sadly, despite this important effort, it is clear that the protection of the water-catchments in karst environment still remains insufficient. The protection zones are only partly effective as water quality problems arise frequently due to agricultural and industrial pollution (Doerfliger and others 1997).
In most European countries three types of protection areas are distinguished, but their definition has no uniformity. The immediate area is often a 10-m radius area around the spring or well, sometimes including swallowholes within the catchment. The inner protection zone is often based on water transit time (10–100 days depending on countries), it can also enclose some preferential infiltration areas. The outer protection area includes the rest of the catchment or at least a 2 km or 400 days transit time limit.

Definition of vulnerability mapping

The term vulnerability was used in the sixties in France, introduced as a scientific term in the specific literature by Albinet and Margat (1970). Since then, several definitions of vulnerability have been presented in the technical literature. In the scope of the development of the EPIK approach, the vulnerability term is defined, as following:
Intrinsic vulnerability represents the inherent hydrogeological and geological characteristics which determine the sensitivity of groundwater to contamination by human activities.
According to Foster and Hirata (1988), Adams and Foster (1992) and Robins and others (1994), aquifer vulnerability is a function of the natural properties of the overlying soil and rock column or unsaturated zone of the aquifer. The risk of groundwater pollution is dependent on both the "natural" vulnerability according to the aquifer properties and to the subsurface contaminant load imposed by human activity. This definition is in agreement with the definition of Foster (1987) and Daly and Warren (1994), as reported in the COST (European Scientific and Technical Cooperation) action 65 final report (Hötzl and others 1995).
Intrinsic vulnerability, as opposed to specific vulnerability, considers all kind of contaminants. (Specific vulnerability is defined for a given contaminant that is characterized through particular properties, that could be different from one contaminant to another. The assessment of specific vulnerability requires consideration ot the characteristics of the aquifer relative to the contaminant and the contaminant itself, in addition to intrinsic hydrogeological and geological characteristics.) Even if the intrinsic vulnerability has only a general meaning in a pollution scenario where specific contaminant take place, according to Andersen and Gosk (1987) and Adams and Foster (1992), the concept of intrinsic vulnerability is necessary to provide a maximum of unbiased information, in order to define protection zones in karst environment. The degradation process are not taken into account in an intrinsic vulnerability approach.
An approach which would include land use, man's activities and potential contamination from sources such as oil spills, leakage from landfills, underground storage tanks, is considered as "risk assessment". It should be used together with the vulnerability mapping as a tool for decision makers and groundwater managers. This "risk mapping" concept is not included in the EPIK approach, presented in this paper.

Conceptual model of a karst aquifer

Our conceptual model of a karst aquifer includes a network of conduits of high hydraulic conductivity (K values$>10^{-1}$ m/s) and of small volume – the karst network

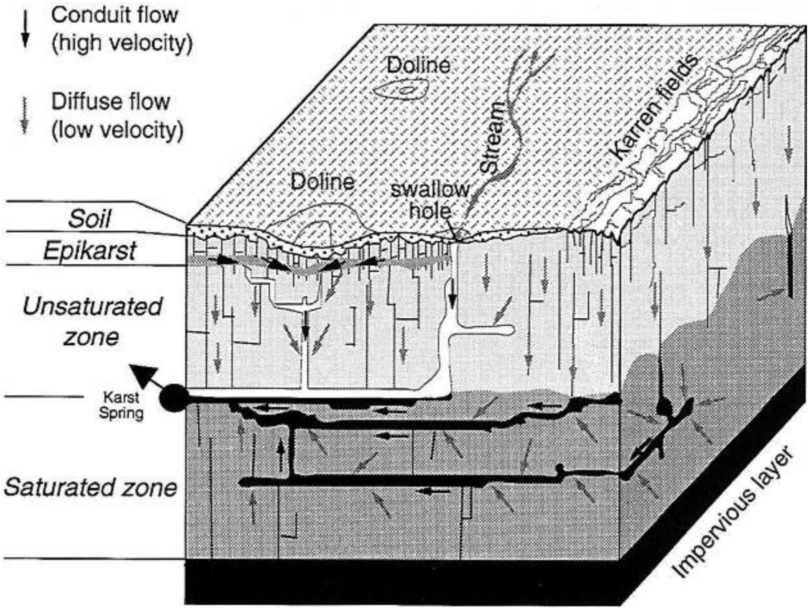


Fig. 1
Conceptual model – scheme – of a karst aquifer used to characterise the vulnerability mapping (Doerfliger and Zwahlen 1995)

– connected to and discharging at an outlet. It is surrounded by and connected with a large volume of low permeability fractured and fissured rock (K values between 10^{-3} and 10^{-7} m/s). The karst network either drains water out of the surrounding rock or recharges it, according to the hydrodynamic state of the aquifer (Fig. 1). We base our model on the facts that karst aquifers are characterised by specific geomorphologic and hydraulic phenomena: the absence of surface or near-surface drainage, the existence of large springs, swallowholes and dolines, the existence of networks of karst solution conduits, the typical spring hydrograph (rapid and violent floods, rapid subsidence and slow tailing), rapid water level variation in some wells, slow response in others and the quick and strong variations in water chemistry as a function of flow.
Recharge does not rapidly flow through the low permeability volumes of the aquifer. This suggests that there are some concentrated infiltration points such as sinkholes directly connected to the karst network. The rest of the quick recharge flows into the conduit network through the epikarst. This epikarst, also called "subcutaneous zone" is an immediate subsurface zone, highly fissured due to the dissolution and pressure release of rock near the ground surface. This zone is subject to extreme weathering (Dodge 1982). Mangin (1973, 1975) defined it as a possible temporary perched aquifer with a base that is essentially a leaky capillary barrier – slow percolation in tight fissures due to the fact that beneath the epikarst, the rock mass has lower permeability – but also enclosing connected pipes that provide effective drainage (Fig. 2). The epikarst layer is not necessarily continuous, its depth may be as thick as 10 m, even in tropical areas. Water flow within the epikarst has a lateral component moving through small conduits towards vertical pipes and a vertical component with slow percolation into small fissures (Williams 1983; Smart and Friederich 1986; Ford and Williams 1989; Klimchouk 1995).

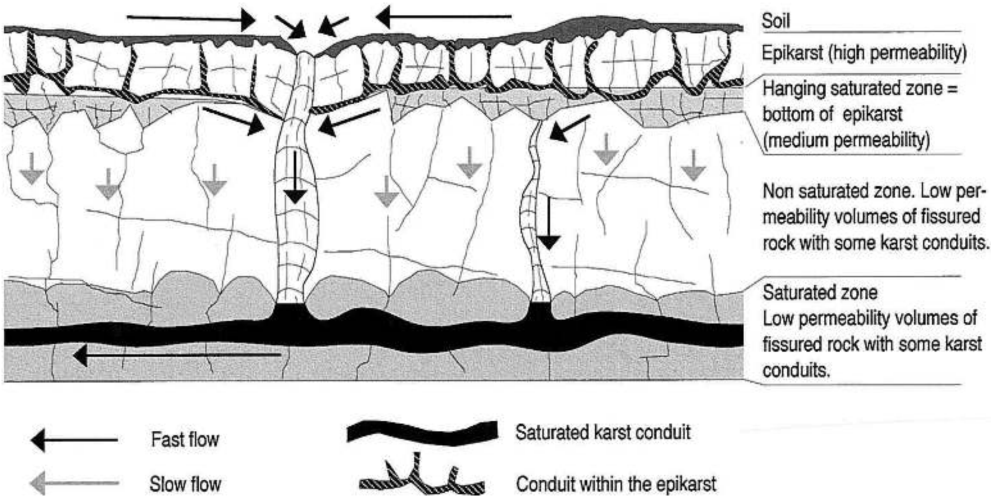


Fig. 2
Water recharge of "low permeability volumes" and of karst conduits by epikarst zone (from Jeannin and Grasso 1995 after Smart and Friedrich 1986)

From conceptual model to vulnerability

Vulnerability of karst waters is a function of direct (mass transport) and retarding (degradation and adsorption) mass-transfer processes. These processes are governed by mass-transfer physical parameters (molecular diffusion, dispersion, sorption capacity, etc.), and also by flow parameters (mainly by the field of flow velocities). In karst systems, the flow velocity field is highly variable due to heterogeneous permeability field. The degradation and/or adsorption processes take time to be effective and therefore the vulnerability of karst water depends essentially on the residence time (or flow velocity) in (through) the system.

Our conceptual karst aquifer model looks directly at the heterogeneity of flow velocities within karst aquifers, which can now be related to vulnerability. The following statements related to the flow system are made:

1. During low water levels (base flow), spring outflow is mainly fed by the water from the low permeability volumes. This water has been resident in this part of the aquifer for a long time. The vulnerability of the spring water which flows during this part of the hydrologic cycle is thus relatively low.
2. During high water level (flood period) most of the water from rainfall events infiltrates into conduits of the epikarst and then flows into the conduit network (Jeannin 1996); this water reaches the spring very quickly. The filtration processes are thus less effective, but compensated for by the dilution of any pollutants in the large amount of water.

Vulnerability depends on the residence time in the different parts of the aquifer. Three main parts can be distinguished:

1. The *endokarst* (conduit network and low permeability volumes) where the flow velocity is high in karst conduits and low in low permeability volumes. A well developed conduit network suggests high vulnerability.
2. The *epikarst* where part of the water is stored and slowly released (low vulnerability) and the rest quickly concentrated into the endokarst conduit network (high vulnerability). The more directly the epikarst is connected to the conduit network, the higher the vulnerability.
3. The *protective cover* (sediments overlaying the limestone) where the residence time essentially depends on the permeability of the cover and of its thickness (among other transport parameters). The permeability of the cover is a function of the cover water saturation range.

The distinction between the three parts presented above is meaningful when the recharge is diffuse (spread off) over the catchment. In some cases, recharge is concentrated in features such as swallowholes and the water infiltrates more or less directly into the endokarst conduit network.

Thus, the characteristics and hydraulic behaviour of the three parts of a karst aquifer allow us to define four attributes that may be used in a multi-attribute method of vulnerability assessment. They are the epikarst, the protective cover, the infiltration conditions and the karst network development.

The four attributes do not include the depth to the water table. This attribute is inappropriate to karst aquifer because of the potential and common immediate and direct recharge of runoff into the karst aquifer via swallowholes and the epikarst conduits without filtration through the unsaturated zone (Ray and O'dell 1993).

EPIK method

The method used to assess the vulnerability of waters of a karst spring over the catchment area is based on our conceptual model. This method is called EPIK, an acronym for Epikarst (E), Protective cover (P), Infiltration conditions (I) and Karst network development (K).

It is a multi-attribute weighting-rating method (overlay and index method) that assesses the groundwater sensitivity of karst terrain in a strict manner. A multiplier, reflecting a relative importance weighting, is assigned to each attribute. The ratings for each class of given attribute are multiplied by the weight related to the attribute and then the products are added up to arrive at a final score. The higher the score, the greater the protection of the area is, i.e. the less vulnerable the area is. At the end, the final numerical score range is assigned to classes of different degrees of vulnerability. One of the first point-count system models called DRASTIC was developed by Aller and others (1987). This point-count system model was chosen for the EPIK method as explained in the next section. The vulnerability assessment with EPIK is made at a scale range from 1:10000 to 1:5000.

Four major steps have to be carried out :

1. The boundaries of the water catchment basin from the spring or well have to be defined on the basis of geology, hydrogeology and tracer tests.
2. The four attributes are assessed, measured (if possible) and mapped. The evaluation is semi-quantitative, by means of classes assigned numbered values.
3. The resulting maps for attributes E, P and I are digitised and integrated into a GIS. The attribute K may globally be assessed for the whole catchment (one overall value), but may also be put on a regional scale according to the geological and tectonic context, and to the speleological knowledge. The GIS can then calculate the vulnerability values for each raster (cell of the map that has been defined) of the catchment basin. Thus, we obtain a map in a format, such that the numbered values of the attribute classes can be combined with an additive procedure. The result is a compilation of the values which effectively is summarised in a vulnerability map.
4. On the basis of this map showing the spatial distribution of the vulnerability, one can determine the different vulnerability classes, respectively the different protection zones.

The most difficult step is the second one, which represents the originality of the EPIK method. In this step, the attributes are combined into a ranking by means of assigning values to the classes. This assessment is made with the help of several methods – direct or indirect – such as tracer tests, geophysics, geomorphologic studies, hydrographs analysis, shallow subsurface probes, interpretation of aerial photographs and so forth. The various indices assigned to each attribute, E, P, I and K are described in the following.

Definition of the attributes and their classes and their characterisation methods

Attribute E : Epikarst

The epikarst zone is located under any consolidated soil. If there is no soil, the morphological features associated with the epikarst are essentially similar to the Karrenfields.

So far, epikarst features have not been studied in great detail. Geomorphologic as well as hydrological characteristics are poorly known. There are no real classification nor investigation tools which allow recognition and mapping of different types of epikarst zones. Further, the epikarst can be heterogeneous over the aerial distribution of a karst aquifer. Therefore, it is difficult to assign detailed classes to different epikarst zones (for example well developed epikarst connected to the karst network, or developed but non-connected to the network, or absence of epikarst, see also Doerfliger 1996).

For this reason and as a first step to address these difficulties, the epikarst zone was characterised indirectly, based on geomorphologic features which can easily be mapped. Three indices have been established over the range of vulnerability:

Table 1
Attribute classes of the Epikarst

Epikarst		Karst morphological features
Highly developed	E_1	Shafts, sinkholes or dolines (from all kinds of genesis), karrenfields, cuesta, outcrops with high fracturing (along roads and railways, quarries)
Moderately developed	E_2	Intermediate zones in the alignment of dolines, dry valleys. Outcrops with medium fracturing.
Small or absent	E_3	No karst morphological phenomena. Low fracture density.

Characterisation of the Epikarst. Mapping the three classes E_1–E_3 is equivalent to mapping the concerned geomorphologic features. In order to do this, topographic maps (1:25000, 1:10000 or 1:5000) are first used to identify and outline these features. Interpretation of aerial photographs allows confirmation and definition of the delineated objects from the topographic map. Observed intersections of lineaments from the aerial photographs or from remote sensing analysis (Landsat photo analysed with GIS) may correspond to highly fractured zones. If no typical geomorphologic features are associated to these zones, they could be mapped under E_2 instead of E_3 to be conservative (Doerfliger 1996).

Attribute P: Protective cover

For this attribute, we include both the soil and other geological overburden such as Quaternary deposits (glacial till, silt, loess, rocks debris), and other non-karst layers, for example, clay and sandstone.

The upper unconsolidated zone overlying the aquifer is commonly regarded as one of the most important attributes in the assessment of groundwater vulnerability. Soil and other geological layers potentially have an important attenuation capacity (Zaporozec 1985) due to specific parameters such as texture/structure, thickness, content of organic matter and clay minerals, degree of water saturation and hydraulic conductivity, in general to various kinds of contaminants. These soil parameters are related to physical, chemical and biological properties that allow attenuation.

The thickness of a soil is strongly related to water residence time. It is an important property when assessing groundwater vulnerability. The thinner the soil, the greater the vulnerability.

As a first approach, in order to be able to assess the vulnerability of a karst water catchment basin, we consider the thickness of the protective cover as basic parameter and its hydraulic conductivity (Doerfliger 1996). We distinguished two cases, both according to the presence of geological layers overlying the limestone and their hydraulic conductivity. To be conservative, we identified four classes with boundary ranges of 20 cm, 100 cm, 200 cm and >200 cm (Table 2).

Characterisation of the Protective cover. This attribute requires field verification using for example boreholes, or auger methods for soil probes.

From published sources such as geological, pedological and topographic maps, geological and regional studies, we can define the areas of the watercatchment with or without overlying geological layers. Aerial photographs and satellite imagery are helpful to determine the soil presence, and probably the thickness (just a scale of sizes) if supplemented with field verification.

With a hand auger, the thickness can be measured directly in the field. If the catchment is not large, it may be cost effective to perform auger holes according on a regular grid. If the catchment is large, the mesh size has to be bigger and it may be necessary to assume similar attributes for similar topography or morphology. This would mean that for a measured thickness at one point, the same thickness is given inside a square of 100-m side, if the point is surrounded by the same morphology (Doerfliger 1996). However, the spatial heterogeneity has to be kept in mind.

Table 2
Attribute classes of the Protective cover

Protective cover		Characterisation A. Soil lying directly on limestone or on some high permeability coarse detritus layers, e.g. rock debris, lateral glacial tills	B. Soil lying on low permeability geological layers, e.g. lake silt, clays
Absent	P_1	0–20 cm of soil	0–20 cm of soil on layers that have a thickness of less than 1 m
↓	P_2	20–100 cm of soil	20–100 cm of soil on layers that have a thickness of less than 1 m
↓	P_3	100–200 cm of soil	<100 cm of soil or >100 cm of soil and >100 cm of layers of low permeability
Present	P_4	>200 cm	>100 cm of soil and thick detritus layers of very low hydraulic conductivity (point-information needs to be checked) or >8 m of clay and clayey silt

Attribute I: Infiltration conditions

The infiltration condition attribute concerns the type of recharge to the karst aquifer. It does not include the recharge in terms of quantity or location. Diffuse and concentrated recharge have different vulnerability inferences. So we identified four infiltration classes, (1) concentrated, (2) diffuse, (3) an intermediate class where runoff may be important and (4) the rest of the catchment.
Recognising concentrated recharge points (I_1) is relatively straight forward. Characteristics of water runoff at the surface of a catchment area have to be identified to assign areas of the watershed to each class of infiltration. Surface runoff tends to concentrate flow which results in higher vulnerability. The runoff coefficient depends on the slope and its vegetation. Steep slopes and poor vegetation result in higher vulnerability, because it is assumed that there is more runoff that will infiltrate in the low relief areas. According to values of runoff coefficient from Sautier (1984), the value distinguishing I_2 and I_3 has been intuitively assigned to a runoff coefficient of 0.22 for meadows and pastures and of 0.34 for cultivated fields (Table 3). This corresponds to a slope of 25% for the meadows and pastures and 10% for the cultivation of fields in the slope direction, respectively. Those limits are arbitrary and pragmatic.

Table 3
Runoff coefficient values for representative Swiss cases. Runoff coefficient is a function of slope and vegetative cover (Sautier 1984). The limit between I_2 and I_3 within a surface catchment and between I_3 and I_4 within the whole catchment is shown by the *grey background*

Slope %	Forest	Meadows-pastures	Cultivated fields in the slope direction
0.5	–	0.005	0.12
1	0.01	0.020	0.13
2	0.02	0.040	0.14
4	0.04	0.070	0.23
6	0.05	0.090	0.27
8	0.06	0.110	0.31
10	0.07	0.130	0.34
15	0.08	0.170	0.40
20	0.10	0.190	0.45
25	0.12	0.220	0.50
30	0.13	0.250	0.55
35	0.14	0.270	0.59
40	0.15	0.290	0.62
45	0.16	0.310	0.65
50	0.17	0.330	0.69

Characterisation of the Infiltration conditions. Obtaining data to classify each area of the catchment requires studying topographic maps. The use of a geographic information system (GIS) can be useful to determine the slope values and low relief areas.

Attribute K: Karst network development

The karst network – or cave system – is a network of solution openings greater than 10 mm in diameter or width. This size is the effective minimum aperture for turbulent flow that will appear as soon as the minimum value is attained under natural conditions (Bögli 1980). The network can be more or less well developed and connected depending on the karst systems considered (Table 5).
The karst network development and its degree of organisation plays an important role on water velocity flow and therefore on the vulnerability.
Because detailed mapping of karst networks is not possible in most cases, one single value per catchment is commonly used.

Table 4
Attribute classes of Infiltration conditions

Infiltration conditions		Characterisation
Concentrated	I_1	Perennial or temporarily losing streams – perennial or temporarily stream feeding a swallowhole or a sinkhole (doline) – water catchment areas of these above mentioned streams, including artificial drainage system.
↓	I_2	Water catchment areas of streams in I_1 (without artificial drainage system) with a slope greater than 10% for cultivated areas and 25% for meadows and pastures.
↓	I_3	Water catchment areas of the I_1 stream (without artificial drainage system) whose slope is less than: 10% for cultivated areas and 25% for meadows and pastures. Low relief areas collecting runoff water and slopes feeding those low areas (slope higher than: 10% for cultivated sectors and 25% for meadows and pastures).
Diffuse	I_4	The rest of the catchment.

Table 5
Attribute classes of Karst network development

Karst network		Characterisation
Well developed karst nework	K_1	Presence of a well developed karst network (network with decimetre to meter sized channels that are rarely plugged and are well connected).
Poorly developed karst network	K_2	Presence of a poorly developed karst network (small conduits network, or poorly connected or filled network, or network with decimetre or smaller sized openings).
Mixed or fissured aquifer	K_3	Presence of a spring emerging through porous terrain. Non-karst, only fissured aquifer.

Characterisation of the Karst network development. Features such as vertical shafts or open cavities leading to a speleological maze (cave) are not always found at the surface in karst catchments. In this case, indirect methods related to analysis of hydrograph data, to artificial tracer tests or to the water quality variation could be used to assess network connectivity.

Three major types of methods can be applied to assess this attribute and its classes, depending on the available data. Differentiation between the classes K_1 and K_2 remains difficult, despite the careful use of the following methods.

Short-term discharge analysis. The reaction time of the spring discharge to recharge events is a simple criteria. We conclude there is a karst network when: (1) a spring response of 2–24 h duration occurs after high intensity precipitation from 15 to 25 mm depending on the season and area, (2) the peak at least twice the base flow, is followed by a rapid decreasing of the discharge and then a long recession flow. This method requires spring discharge recording over only a few months. It can also be applied when discharge values are approximate.

Long-term discharge analysis. Bakalowicz and Mangin (1980) showed that the apparent heterogeneity of karst aquifers is not the result of a random juxtaposition of different void types, but stems from voids distribution with a certain hierarchy, around a drainage axis. Considering the karst drainage system as characterised by an impulse function that transforms the input – precipitation – to hydrograph responses at springs, the analysis of this functions can be related to "effectiveness" of the drainage, i.e. connectivity of the network. The analysis of flood and base flow recession was proposed by Mangin (1982) who identified five principal karst systems using spectral and correlation analysis. The class K_1 of the EPIK method is similar to Mangin classes I–III, the class K_2 to IV and K_3 to V.

This method requires hydrographs of at least one entire cycle. Further, this classification based on the results of recession curves analysis may be not unique as some parameters may vary considerably with time. For the same aquifer, different Mangin classes may be obtained according to Jeannin and Grasso (1994). This is due to the fact that the decreasing limb of the hydrograph is influenced by variation in precipitation, degree of aquifer saturation before the rising limb and catchment size. However, the characterisation of the karst network by EPIK method is to date approximate, and Mangin's method will provide satisfactory results in most cases.

Artificial tracer tests. Flow velocity values obtained from artificial tracer tests may identify and characterise karst network. The transit velocity is calculated from the first arrival time or the mean peak time. This velocity depends on the hydrodynamic conditions and on the development of the karst network.

If the mean transit velocity from a swallowhole (generally connected to the karst network) is higher than 15 m/h at low water stages and 75 m/h at high water, this would imply that a karst network is present. Lower velocities do not obviously imply the absence of a karst network.

Evaluation of the protection factor – vulnerability degree

In order to quantitatively evaluate the protection factor of each cell at a given site, a numerical rating has been set up based on points using the EPIK attributes. The system contains two major parts: weighting and rating. The protection factor F_p is calculated with the following basic formula, which represents a strongly simplified hydrogeological model. For each cell, we compute:

$$F_p = \alpha \times E_i + \beta \times P_j + \gamma \times I_k + \delta \times K_l \quad (1)$$

NB Low F_p corresponds to high vulnerability.
To assign a weighting value to α, β, γ, δ and to rate E_i, P_j, I_k and K_l, we carried out several empirical tests. Intuitively, according to the definition of the attributes and their classes, a doline, an uncovered karst area, a concentrated infiltration and a well developed karst network are the worst vulnerability case.
Then the following situations have also been taken into consideration:

1. A stream sinking into a swallowhole (I_1) has a high degree of vulnerability, independent of the protective cover.
2. A dry valley (E_2) is as vulnerable as a low topographical point where runoff is collected.

The following values have been assigned to the different E_i, P_j, I_k and K_l classes (Table 6).
The values of the weighting factors (α, β, γ, δ) range from 1 to 3 (Table 7).
As Epikarst and Infiltration conditions cannot play an important protection role on the karst groundwater, their relative weights have to be important, towards a lower vulnerability degree. When E_3 and I_3 or I_4 are located on the same pixel, their weight in the resulting protection factor is important, independently of the classes of P and/or K attributes. As the role of the protective cover attribute is maybe overestimated taking into account only the thickness, its relative weight is in between. The Epikarst relative weight (α) is the same as the Infiltration conditions weight (γ). The choice of these weighting factors and of the values assigned to the different classes of each attributes is empirical.
Calculating the protection factor F_p for the various possible combinations, we obtain then the results presented in Table 8.

Table 7
Relative weights attributed to the factors α, β, γ and δ

Epikarst (E)	Protective cover (P)	Infiltration conditions (I)	Karst network (K)
α	β	γ	δ
3	1	3	2

Field application: Saint-Imier test site (Swiss Jura)

Vulnerability mapping using the EPIK method was carried out within the catchment areas of the springs used by St-Imier township for public watersupply (Canton Bern).

The St-Imier water catchment

The St-Imier catchment has an area of about 110 km^2. The aquifer is Sequanian to Portlandian (Malm) limestone which ranges in thickness from 200 m to 400 m. The underlying aquiclude is Argovian marl. In the 1980s, protection zones were established only in the northern part of the catchment. Their limits were based on practical instructions prepared specifically for this purpose by the Federal Office of Environment, Forests and Landscape (FOEFL 1977, revised 1982). An S3 protection zone covers essentially all the area that was considered (Fig. 3a). However, despite establishing the protection areas, pollution from liquid manure typically occurs four times a year following snow melt and violent thunderstorms with heavy rainfall.
In order to address this water quality problem, the EPIK method has been applied on this site to re-establish groundwater protection areas. Mapping the various attributes resulted in a vulnerability map (Fig. 4 and 5). The relationship between the protection factor F_p and the groundwater protection areas S is given on Table 9. In Fig. 3b, the suggested groundwater protection areas for the St-Imier water catchment are shown. The comparison between the previous zoning shown in Fig. 3a and the newly proposed (Fig. 3b) indicates that S1 and S2 areas are more numerous with the multi-attribute vulnerability EPIK method at the catchment scale. Also they can be attributed to sensitive locations. These newly suggested ar-

Table 6
Weighting of the classes of the attributes E, P, I and K. The lower the value of the number, the higher the sensitivity to contamination

Epikarst			Protective cover				Infiltration conditions				Karst network		
E_1	E_2	E_3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

Table 8
Calculation of the protection factor $F_p = 3E_i + 1P_j + 3I_k + 2K_l$; – incompatible combination

Well developed karst network: $K_1 = 1$

	Infiltration conditions											
	$I_1 = 1$			$I_2 = 2$			$I_3 = 3$			$I_4 = 4$		
Epikarst→	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$
Prot. cover												
$P_1 = 1$	9	15	18	12	18	21	15	21	24	18	24	27
$P_2 = 2$	10	16	19	13	19	22	16	22	25	19	25	28
$P_3 = 3$	–	17	20	14	20	23	17	23	26	20	26	29
$P_4 = 4$	–	18	21	15	21	24	18	24	27	21	27	30

Poorly developed karst network: $K_2 = 2$

	Infiltration conditions											
	$I_1 = 1$			$I_2 = 2$			$I_3 = 3$			$I_4 = 4$		
Epikarst→	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$
Prot. cover												
$P_1 = 1$	11	17	20	14	20	23	17	23	26	20	26	29
$P_2 = 2$	12	18	21	15	21	24	18	24	27	21	27	30
$P_3 = 3$	–	19	22	16	22	25	19	25	28	22	28	31
$P_4 = 4$	–	20	23	17	23	26	20	26	29	23	29	32

No karst network: $K_3 = 3$

	Infiltration conditions											
	$I_1 = 1$			$I_2 = 2$			$I_3 = 3$			$I_4 = 4$		
Epikarst→	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$	$E_1 = 1$	$E_2 = 3$	$E_3 = 4$
Prot. cover												
$P_1 = 1$	13	19	22	16	22	25	19	25	28	22	28	31
$P_2 = 2$	14	20	23	17	23	26	20	26	29	23	29	32
$P_3 = 3$	–	21	24	18	24	27	21	27	30	24	30	33
$P_4 = 4$	–	22	25	19	25	28	22	28	31	25	31	34

Table 9
Allocation of protection factors to groundwater protection areas S1, S2 and S3

Vulnerability areas	Protection factor F	Protection areas Si
Very high	F lower or equal to 19	S1
High	F between 20 and 25	S2
Moderate	F higher than 25	S3
Low	Presence of P4	The rest of the water catchment

eas would result in effectively more restrictive land-use rules than those suggested previously.
The validation of the weighting system was done by carrying out dye tracer tests in four areas of varying degrees of vulnerability (high–low) in the St-Imier water catchment and by investigating deeply the nature of the epikarst (fracturation) with electromagnetic geophysical survey (Doerfliger 1996). The results of the validation are consistent with the vulnerability factor attributed to the tested areas.

Conclusion and perspectives

The proposed approach for the delineation of groundwater protection areas in karst environments based on vulnerability mapping effectively complements the complex hydrogeological behaviour of karst systems. We used four attributes integrating the unique character and responses

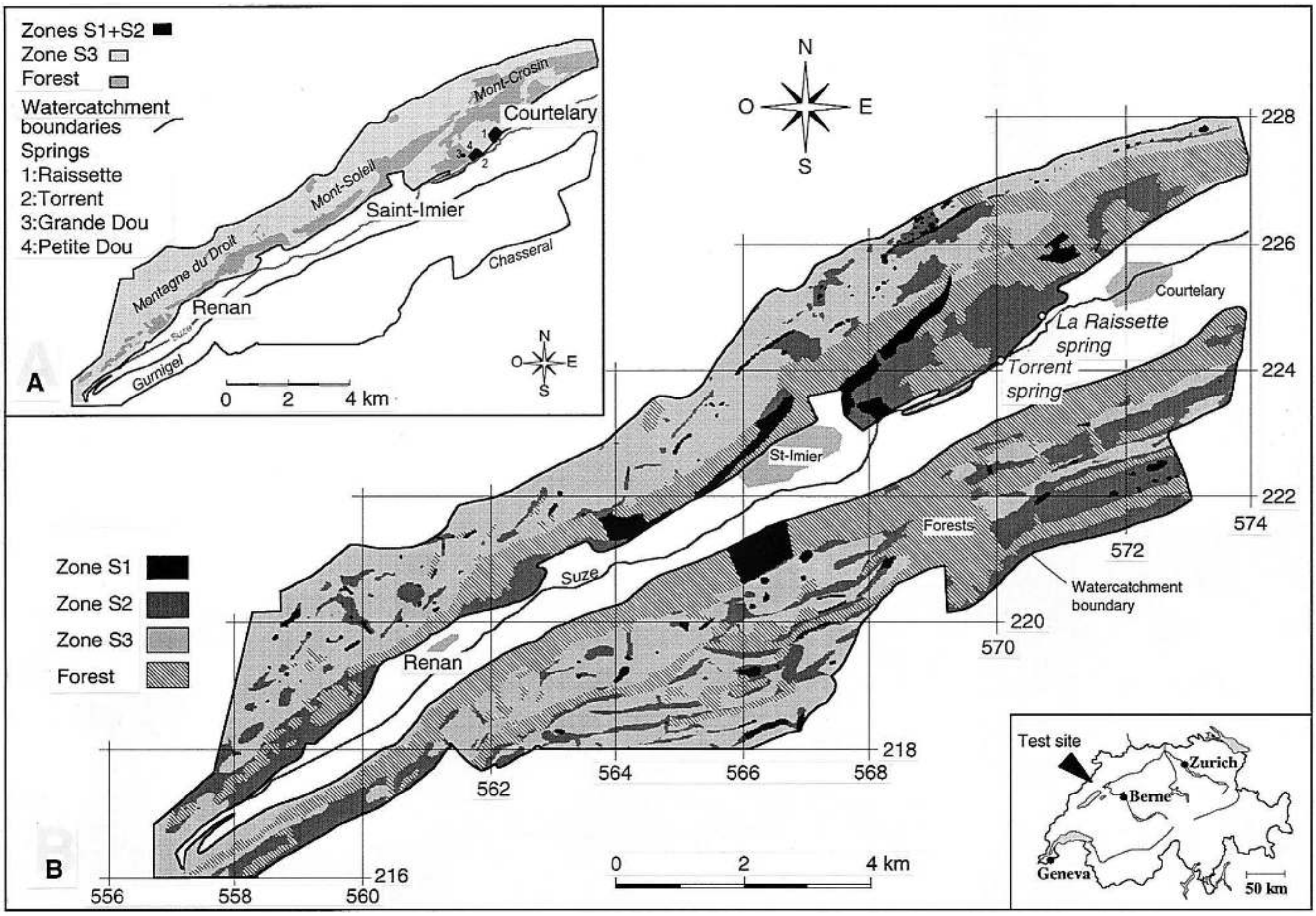


Fig. 3
Groundwater protection areas of St-Imier catchment (Folded Jura, Canton Bern, Switzerland). **A** previous established zones in the northern part of the water catchment, **B** suggested groundwater protection zones, resulting from the use of the multi-attribute approach of vulnerability mapping, the EPIK method

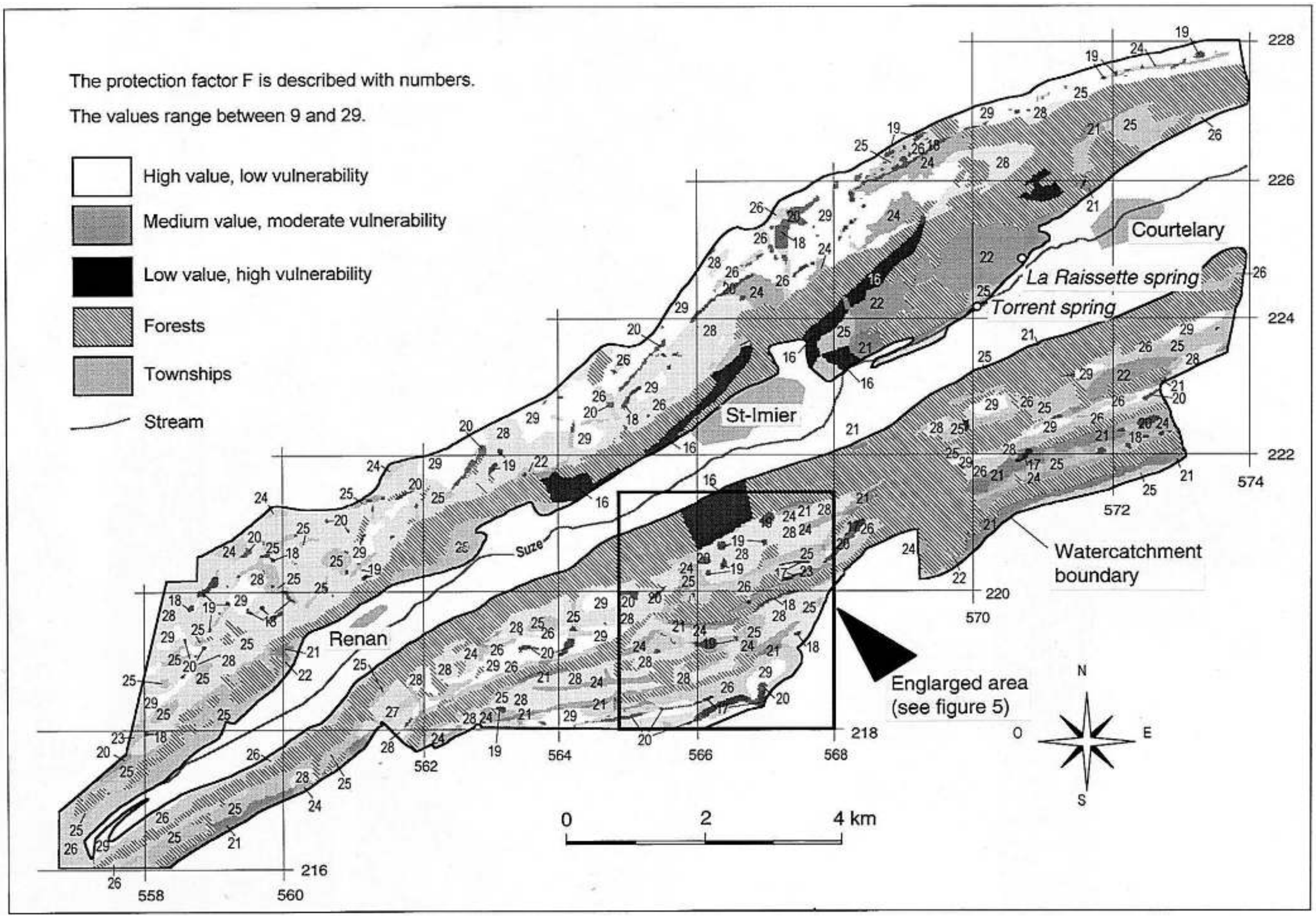
Fig. 4 ▶
Vulnerability map of St-Imier catchment (Folded Jura, Canton Bern, Switzerland). The vulnerability is expressed by the protection factor F_p; its values range from 9 to 29. The value of the protection factor is written on white capitals inside of black raster

of karst hydrogeology. The Epikarst, Protective cover, Infiltration conditions and Karst network development are attributes related to the vulnerability mapping of karst catchments. Vulnerability maps based on these four parameters are a new step forward to better determination of groundwater protection areas in karst environment. The example presented here, as other applications indicate clearly that the EPIK method is feasible and readily applied with proper input data.

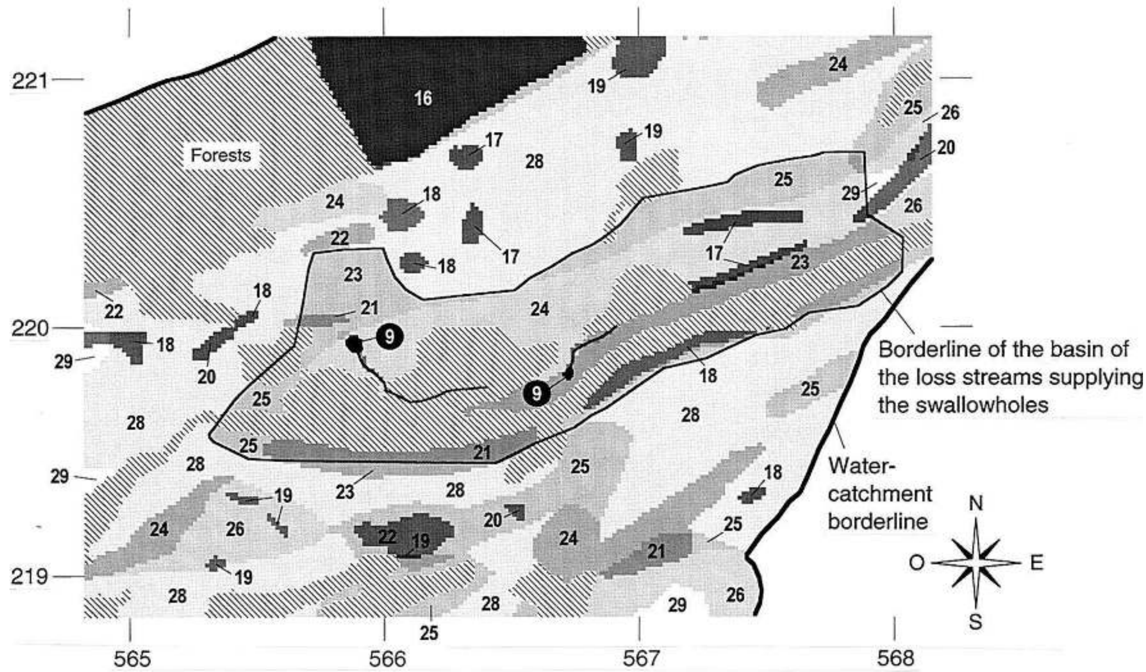
Nevertheless, although the concept underlying this new map is an improved approach for the assessment of protection zones, further research is needed. Especially the characterisation of the epikarst needs improved indirect methods such as infiltration tests, artificial tracer tests and geophysics. Further characteristics of the soil and protective cover such as CEC (Cation Exchange Capacity) and AEC (Anion Exchange Capacity) should also be checked. In addition, the EPIK method does not take into account some dynamic characteristics, such as temporal variations of infiltration.

Using geographical information systems (GIS) to study various test sites, for example at St-Imier, allowed us to develop different quantitative approaches with the method and to carry out useful sensitivity tests. GIS also simplifies construction of a vulnerability map. Using the analysis of the digital topographic model (DTM), GIS allows one to determine infiltration condition classes automatically.

Fig. 5 ▶
Zoom on an area of St-Imier catchment vulnerability map



Watercatchment of St-Imier springs (Extract of the vulnerability map)



$Fp = 3\ Ei + Pj + 3\ Ik + 2\ Kl$, with $i=1, 3, 4$; $j= 1, 2, 3, 4$; $k=1, 2, 3, 4$ and $l=1, 2, 3$.

Groundwater contamination in karst regions is not bound to happen. For better protection of these resources, priority has to be given to prevention. Groundwater protection zones are feasible and efficient. This new approach to vulnerability mapping constitutes a basis for defining realistic and effective protection zones in karst regions.

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